# THE EFFECT OF SOLUTION CONCENTRATION AND COMPOSITION ON SOIL HYDRAULIC CONDUCTIVITY

By

HABIB HIZEM

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

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THE EFFECT OF SOLUTION CONCENTRATION AND
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CONDUCTIVITY

Thesis Approved:

James M. Davidson
Thesis Adviser

Lester W. Reed

Fenton Gray

D. D. Durham
Dean of the Graduate College

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# CHAPTER I

## INTRODUCTION

Good irrigation practices in agriculture still remain one of man's primary concerns. This is especially true in arid and semi-arid regions where rainfall is inadequate for crop production and where feeding an increasing population poses a significant problem. One of the major problems in irrigation is salinity control. However, where salinity problems already exist, reclamation of the salt affected soil is necessary before a profitable irrigation program can be initiated.

In an irrigation project the necessity of maintaining a salt balance in the irrigated soil must be kept in mind in order to establish a desirable soil permeability and a suitable salt condition for plant growth. This means that the amount of salt entering the soil in the irrigation water must be equal to the amount of salt leaving the soil in the drainage water over the same period of time. Also, the relative composition of the salt in the soil must not be changing in an undesirable way.

In a soil-water system where an equilibrium exists between the adsorbed cations and the soil-water solution, the equilibrium conditions may or may not be altered by the irrigation water. If the cations in solution and the cations already adsorbed by the soil particles are of unequal valence like calcium and sodium, the direction and extend of exchange will depend not only upon the valence but also upon the concentration. At a high sodium concentration calcium may be replaced, this displacement will cause a decrease in the hydraulic conductivity upon dilution of the sodium concentration. In general, a low valence cation tends to be displaced by a cation of higher valence. In a soil water system calcium will replace sodium and will be adsorbed. This adsorption will increase the permeability of the soil.

Soils in arid and semi-arid regions often have a high exchangeable sodium percentage before being irrigated. For this reason the quantity and composition of electrolyte in the irrigation water should be given a greater consideration because salinity can make soils unproductive.

The purpose of this study was to investigate the effect of electrolyte concentration on the hydraulic conductivity when the soil had been previously saturated with calcium or sodium. The hydraulic conductivity using various concentrations and combinations of NaCl and $CaCl_2$ were measured.

# CHAPTER II

## LITERATURE REVIEW

It has been illustrated many times in the previous studies of Kelly (7) and Fireman (6) that the rate of water flow through sodic soils depends upon the electrolyte concentration of the water. These studies have shown that the permeability of such soils may decrease rapidly by leaching with a low-salt water but an increase in the concentration of the infiltrating water will increase the rate of water intake. Kelly (7) was among the first to study the chemical effect of saline irrigation water on soils. He described the effect of such practices on the physical properties of the soil. He reported that there were positive advantages to the use of saline water for the reclamation of sodic soils. The high concentration of salts prevented the dispersion of the system and improved the water transmission and leaching of the soil, but the permeability will be reduced when an irrigation water of a much lower salt concentration was substituted. Fireman and Bodman (6) and more recently Quirk and Schofield (10) pointed out the advantages of using high-salt water for reclamation purposes. They found that soils having high exchangeable sodium percentage will remain permeable to water with a high electrolyte concentration.

Fireman (6), working with a sandy loam soil, obtained a high and constant permeability when a 800 ppm $CaCl_2$ solution was used as the percolating liquid, however, when distilled water was used the permeability decreased. A NaCl solution of 4500 ppm decreased the soils permeability, but the soil-water flow rate was always higher than that measured with distilled water.

Quirk and Schofield (10) worked with salt systems to determine the change in permeability of the soil with decreasing solute concentrations. For sodium saturated clay, a uniform rate of flow was obtained with 0.5N NaCl solution, however, when the concentration was reduced to 0.25N NaCl the clay became visibly swollen and impermeable. They suggest that this decrease in permeability was due to swelling and dispersion of the clay as a result of the double layer repulsion between the surfaces of the individual particles which pushed them apart.

Quirk (10) has shown that the reduction in hydraulic conductivity can be attributed to the crystalline swelling of montmorillonite. He then concluded that the mechanism for the reduced permeability was the result of three processes.

(1) Swelling which results in the blocking or partial blocking of the larger conducting pores.

(2) The stability of soil aggregates is reduced because of the stress from unequal swelling throughout the soil mass.

(3) Dispersion or deflocculation occurs when the repulsive forces are sufficient to produce a strong net repulsive force.

Further studies on the effect of electrolyte concentrations on permeability were reported by Reeve and Bower (11) who outlined procedures for the reclamation of sodic soils based upon "valence-dilution effect." This procedure was based upon the theory of cation exchange equilibrium. They found that the flocculative effect of high electrolyte concentrations was responsible for the increase in permeability.

In fact, when a small amount of salt is added to the soil-water solution soil particles stick together forming flocs. The attractive forces between all the atoms of one particle and all the atoms of another particle are called van der Wall's forces. However, this particle attraction is counteracted by a repulsive force between the particles. Because clay particles carry a net negative electric charge, this repulsive force is of an electrical nature. The repulsive force depends on the presence or the absence of salt in the soil-water solution, and decreases as the ion concentration increases. The attractive or van der Wall's force is constant. The particle charge and the equivalent amount of ionic charge accumulated in the liquid near the particle surface form what is referred to as an electrical double layer. The ions in solution are attracted by the oppositely charged clay surface. At the same time these ions have a tendency to diffuse away from the surface towards the bulk of the solution where the concentration is lower. When a flocculating electrolyte is added to the soil-water system, the diffuse double layer is compressed towards the clay surface. The electric potential or Zeta potential in the double layer is considered a measure of the particle repulsion. Upon the addition of an electrolyte, the Zeta potential decreases due to the compression of the double layer and the decrease in the repulsive forces. Consequently the stability of the dispersed system decreases and the phenomenon of flocculation occurs.

The forces of attraction between the cations and the clay particles are of a magnitude comparable to Coulomb's attractive forces. The compression of the double layer is governed by the concentration and valence of the ions. The higher the concentration and the higher the valence of the cations the more the double layer is compressed. For example, $CaCl_2$ is a more capable flocculant than NaCl at the same concentration.

When cations are adsorbed by the soil particles they may be replaced by other cations that occur in the soil solution. Numerous equations have been derived to describe cation exchange equilibrium in soil-water system. Bower (4) formulated an expression similar to that proposed by Gapon in which two heterovalent cations are involved.

$$\frac{\left[Na_{ad}\right]^{2}\left(Ca^{++}\right)}{\left(Na^{+}\right)^{2}\left[Ca_{ad}\right]} = K$$

Ca and Na are expressed in meq/l

K is the equlibrium constant

Recently Reeve and Doering (12) suggested a practical method for the reclamation of sodic soil. Their procedure was to achieve a partial reclamation with high-salt water and successive dilution with the application of gypsum followed by an excess of irrigation water. The high salt water was to flocculate and increase soil permeability as well as a source of divalent cations. They found that the high salt water dilution method using salty water was effective in reducing the exchangeable sodium from about 75 percent to 23 per cent in the upper 90 cm of the soil profile. They believe that the high salt water dilution method was effective in maintaining high permeability. However, its feasibility depends heavily upon the availability of high salt water in which the divalent cation concentrations are 30 per cent or more of the total salt concentration. Also, the amount of water that must pass through the soil profile increases exponentially as the divalent cation fraction decreases.

McNeal and Coleman (9) studied the qualitative effects of different salt solutions on soil hydraulic conductivity. They established a general relationship between soil clay mineralogy, hydraulic conductivity, and solution composition for predicting the relative hydraulic conductivity value under sodic conditions. They point out that permeability decreases with decreasing electrolyte concentration and increasing the sodium adsorption ratio of the percolating solution. Also, the decrease is more pronounced for soils high in montmorillonite and the decrease was irreversible upon the application of high salt except for soils containing more than 10% montmorillonite. Data (Fig. 1) show that at the high salt concentration with SAR = $\infty$ the hydraulic conductivity remains high in the Pachappa sandy loam and in Waukena clay loam, they also indicated that exchangeable sodium percentage of 15 or greater can generally be tolerated before reductions in hydraulic conductivity will occur providing the total concentration of the percolating solution exceeds 3 meq/l. They also found an excellent correlation between clay swelling and hydraulic conductivity. They point out that the hydraulic conductivity decreases were not only due to swelling but also due to particle dispersion and translocation.

It appears from the previous studies that swelling is the dominant mechanism for hydraulic conductivity decreases in soils containing large amounts of expansible minerals, while dispersion and particle translocation would be the dominant mechanism for permeability decreases in coarse textured soils. Whatever the mechanism for the hydraulic conductivity decrease, it is evident that solution concentration and composition are responsible for the change in the permeability.

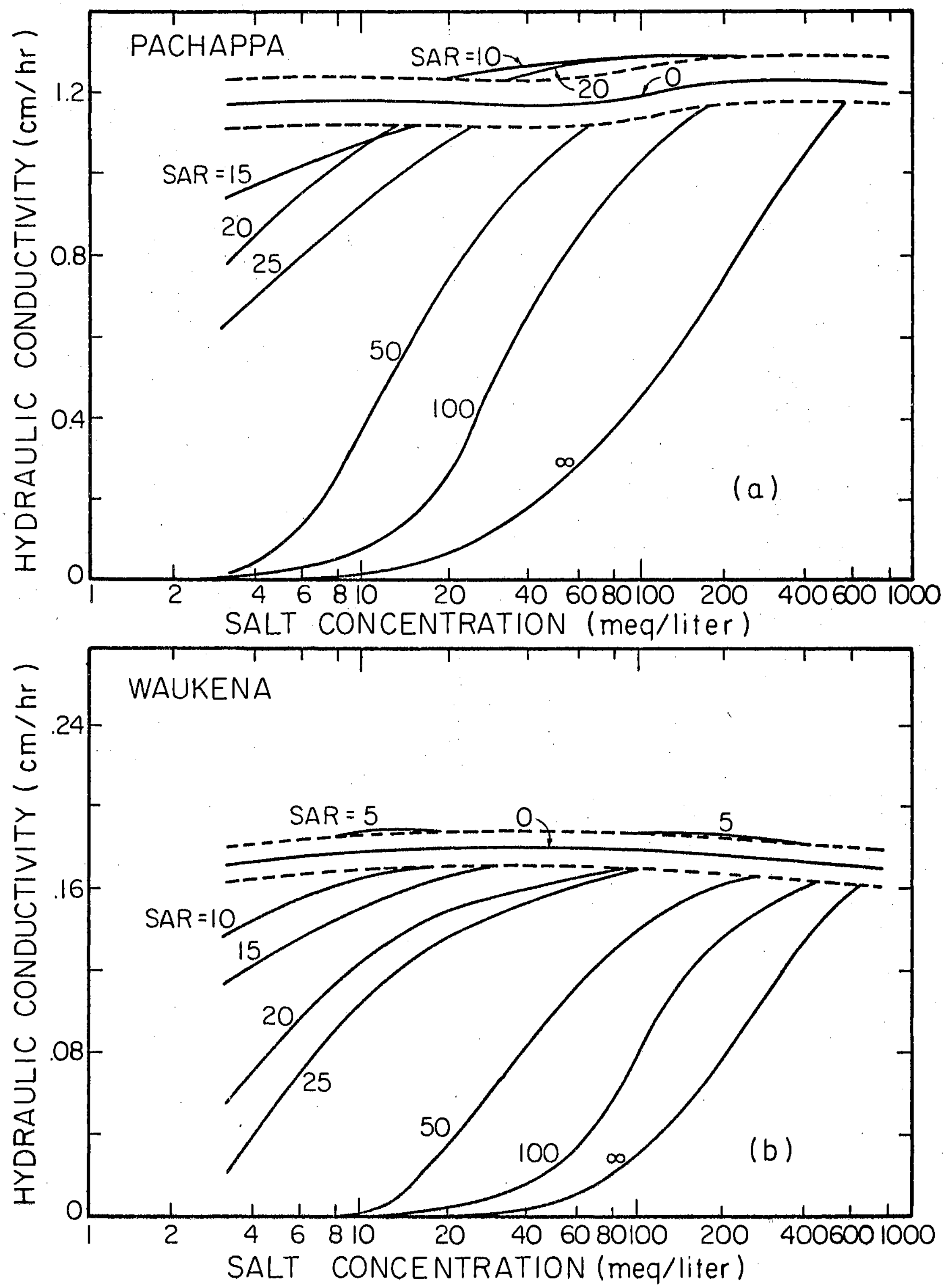


Figure 1. Hydraulic Conductivity Vs. Salt Concentration for (A) Pachappa Sandy Loam and (B) Waukena Clay Loam.

The present study was designed to provide detailed information on the effect of electrolyte concentration and composition on the hydraulic conductivity of a Norge loam.

# CHAPTER III

## MATERIALS AND METHODS

The soil used for this study was a Norge loam from the Oklahoma State University Experiment Station near Perkins.

### Soil Saturation With Sodium

A soil sample consisting of 1500 gm of dry soil was added to 1500 ml of sodium acetate (0.5N). After a period of 4 hours the suspension was filtered using a large vacuum funnel fitted with medium porosity filter paper. The filtered solution was discarded and the remaining soil was wetted again with 1500 ml of sodium acetate solution (0.5N). After a period of 4 hours the suspension was then filtered as before, and the remaining soil mixed with 1500 ml of sodium sulfate (0.01N). This procedure was followed for two additional washings with 0.01N sodium sulfate. Following the final washing the soil was air dried and ground to pass through a 2 mm sieve.

### Soil Saturation With Calcium

A soil sample consisting of 1500 gm of dry soil was added to 1500 ml of calcium acetate (0.5N). After a period of 4 hours the suspension was filtered. The filtrate was discarded and the remaining soil was wetted again with 1500 ml of calcium acetate (0.5N). This procedure was then repeated 3 more times using calcium sulfate (0.01N) instead of calcium acetate until complete soil saturation with calcium. Both soil samples were then air dried, ground and passed through a 2 mm sieve. Each soil sample was packed in a separate plastic column to a specific bulk density of 1.6 gm/cm$^3$.

Flow Apparatus

Figure 2 shows a schematic drawing of the flow cell used. The soil chamber material was acrylic plastic. The length and diameter of the column were 30 cm and 7.5 cm, respectively. A porous ceramic disc was sealed to the column end with epoxy resin. Five tensiometers were placed in the soil chamber 5 cm apart and served to determine the soil-water pressure distribution in the soil column. Inflow volumes were measured by a burette and the rate of water flow was maintained constant at 0.5 ml/minute by the use of an electric pump. The effluent was collected for 10 minute periods by the use of an automatic fraction collector. The cation exchange capacity of the Norge loam was 6 meq/100 gm. The CEC was measured using the procedure recommended by Bower in the USDA Agricultural Handbook No. 60 (14). Mechanical analysis of the soil studied was measured using the hydrometer method described by Bouyoucos (3) and the USDA Size Range System.

TABLE I

MECHANICAL ANALYSIS OF DISTURBED SOIL SAMPLE

| Soil type | Sand $>50u$ | Silt 2u to 50u | Clay $<2u$ |
|---|---|---|---|
| Norge loam | 51.5 | 31.4 | 17.1 |

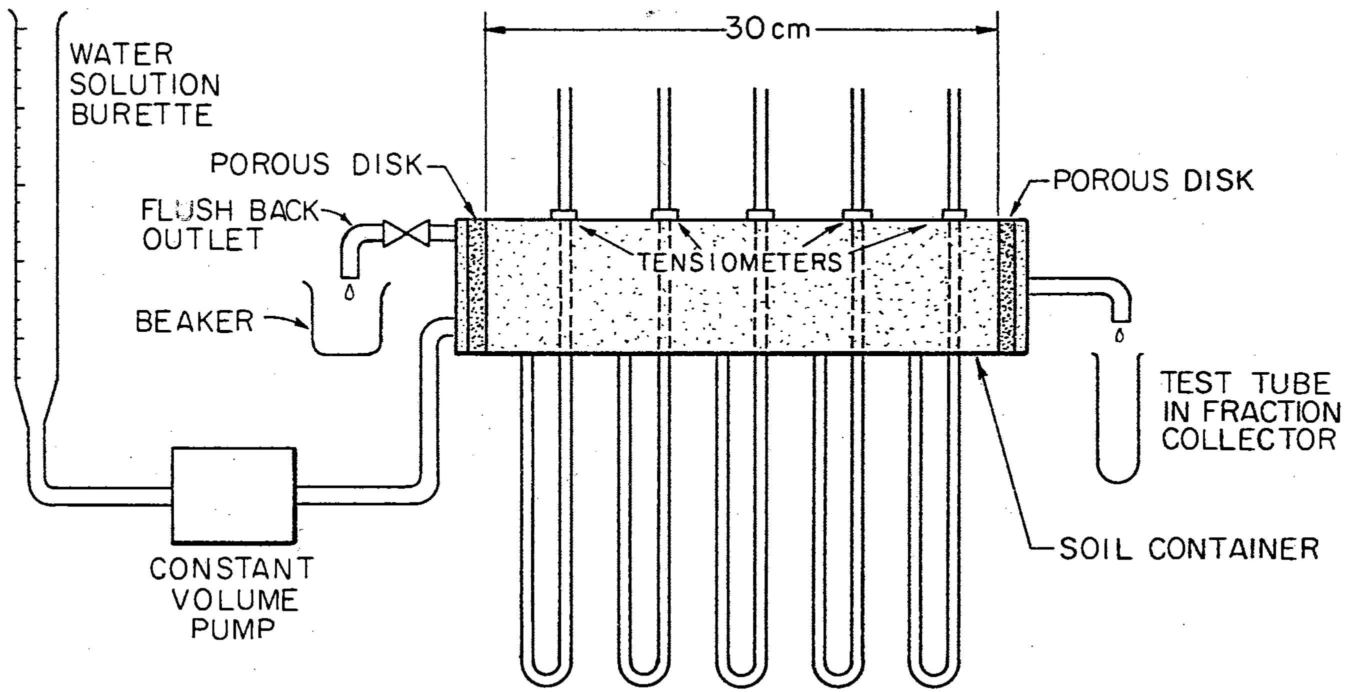


Figure 2. Flow Cell and Associated Assembly for Measuring Soil-Water Pressure.

Soil extracts and effluent samples were analyzed for calcium and sodium by the procedure outlined by Richards (14). Sodium and calcium concentrations in the effluent were measured using the atomic absorption spectrophotometer (2). Chloride concentrations were determined by the Mohr titration method (14) using silver nitrate (0.1N). Hydraulic conductivity values were calculated from the difference in pressure between two given tensiometers and the application of Darcy's equation.

$$\frac{Q}{At} = -K \frac{\Delta H}{\Delta X}$$

Q = volume in ml per minute

t = time in minutes

A = area in $cm^2$

$\Delta H$ = difference of pressure in cm

$\Delta X$ = distance in cm

Calcium Saturated Soil

A calcium saturated soil was packed into the plastic column and wetted with $CaSO_4$ (0.01N). The exchange complex was brought into equilibrium by passing the calcium sulfate solution (0.01N) through the soil column for 24 hours at the rate of 1 ml/minute. Then 6000 ml of sodium chloride at concentrations of 500, 250, 100 and 50 meq/l were applied to the sample in sequence. A flow rate of 0.5 ml/minute was maintained throughout the study. Data for calculating the change in hydraulic conductivity were taken and effluent samples were collected for determination of chloride and sodium.

To determine the reversibility of the hydraulic conductivity decreases which occurred, another calcium saturated soil column was packed in the plastic chamber and wetted with calcium sulfate (0.01N) for 24 hours at the rate of 1 ml/minute, then 2000 ml of sodium chloride (0.1N) was applied at the rate of 0.5 ml/minute. Following the NaCl washing a solution of 0.01N $CaSO_4$ was reapplied at the rate of 0.5 ml/minute.

Sodium Saturated Soil

A soil sample of Norge loam was saturated with sodium by flowing a sodium sulfate solution (0.5N) through the soil for 48 hours at the rate of 1 ml/minute. Following this pretreatment a series of $CaCl_2$ and NaCl solutions of 1000 ml each were applied in sequence at a rate of 0.5 ml/minute. $CaCl_2$ concentration was maintained constant in the four series.

TABLE II

SOLUTION CONCENTRATION AND COMPOSITION

| Series | Vol. (ml) | $CaCl_2$ (meq/l) | NaCl (meq/l) | Total Concentration (meq/l) | SAR | ESP |
|---|---|---|---|---|---|---|
| 1 | 1000 | 10 | 90 | 100 | 40 | 36.6 |
| 2 | 1000 | 10 | 50 | 60 | 22 | 23.7 |
| 3 | 1000 | 10 | 10 | 20 | 4.5 | 5 |
| 4 | 1000 | 10 | 5 | 15 | 2.2 | 3 |

Another soil sample was packed in the plastic column and wetted with sodium sulfate solution (0.5N) for 48 hours at the rate of 1 ml/minute. Then 4 series of solutions were prepared from $CaCl_2$ and NaCl of 1000 ml each and applied in sequence at a rate of 0.5 ml/minute.

TABLE III

SOLUTION CONCENTRATION AND COMPOSITION

| Series | Vol. (ml) | $CaCl_2$ (meq/l) | NaCl (meq/l) | Total Concentration (meq/l) | SAR | ESP |
|---|---|---|---|---|---|---|
| 1 | 1000 | 130 | 470 | 600 | 50 | 45 |
| 2 | 1000 | 65 | 235 | 300 | 41 | 38 |
| 3 | 1000 | 32 | 118 | 150 | 29 | 30 |
| 4 | 1000 | 16 | 59 | 75 | 21 | 24 |

Hydraulic conductivities values were calculated for each series. Sodium adsorption ratio (SAR) was calculated using the formula

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

Exchangeable sodium percentages were also calculated from the formula outlined in the USDA Agricultural Handbook No. 60 (14).

$$ESP = \frac{100\ (-0.0126 + 0.01475\ SAR)}{1 + (0.0126 + 0.01475\ SAR)}$$

The exchange constant K for calcium replacing sodium was determined. $CaCl_2$ at different levels of concentrations (0.01N, 0.1N, 0.5N and 1.N) was used to replace the sodium on the sodium saturated soil. The amount of calcium adsorbed is calculated by substracting the concentration of $CaCl_2$ in the solution from its initial concentration for each concentration.

For each soil column studied seven soil samples, 5 cm apart, were collected with length and analyzed for calcium and sodium using the procedure recommended by Bower (14).

CHAPTER IV

# RESULTS AND DISCUSSION

## A. Effects of Solution Concentration on Soil Permeability

Because equilibrium in soils containing sodium and calcium is of particular interest from the standpoint of practical application, information about the exchange constant of the soil studied were considered important. The equilibrium data for calcium adsorption at various concentrations (0.01N,0.1N, 0.5N, 1.N) are presented in Figure 3. The exchange constant K for a specific concentration is the slope of the curve at that concentration.

After 6000 ml of NaCl (0.5N, 0.25N, 0.1N and 0.05N) of 1500 ml each concentration have passed through the calcium saturated soil column; the analysis of the collected effluent shows that chloride appears first in the effluent owing to the exchange of sodium for the calcium ions (Fig. 4). The area between the chloride curve and the sodium curve should be used to determine the cation exchange capacity of the Norge loam. Analysis of the soil with length shows that calcium ions still remain in the soil-water system (Fig. 5). This illustrates that there may be some positions in the soil matrix that are not in equilibrium with the flowing system. It may also illustrate the fact that divalent cations are strongly attracted by clay particles.

Hydraulic conductivity values for $K_4$, the fourth position in the soil column, are presented in Figure 6 as a function of NaCl

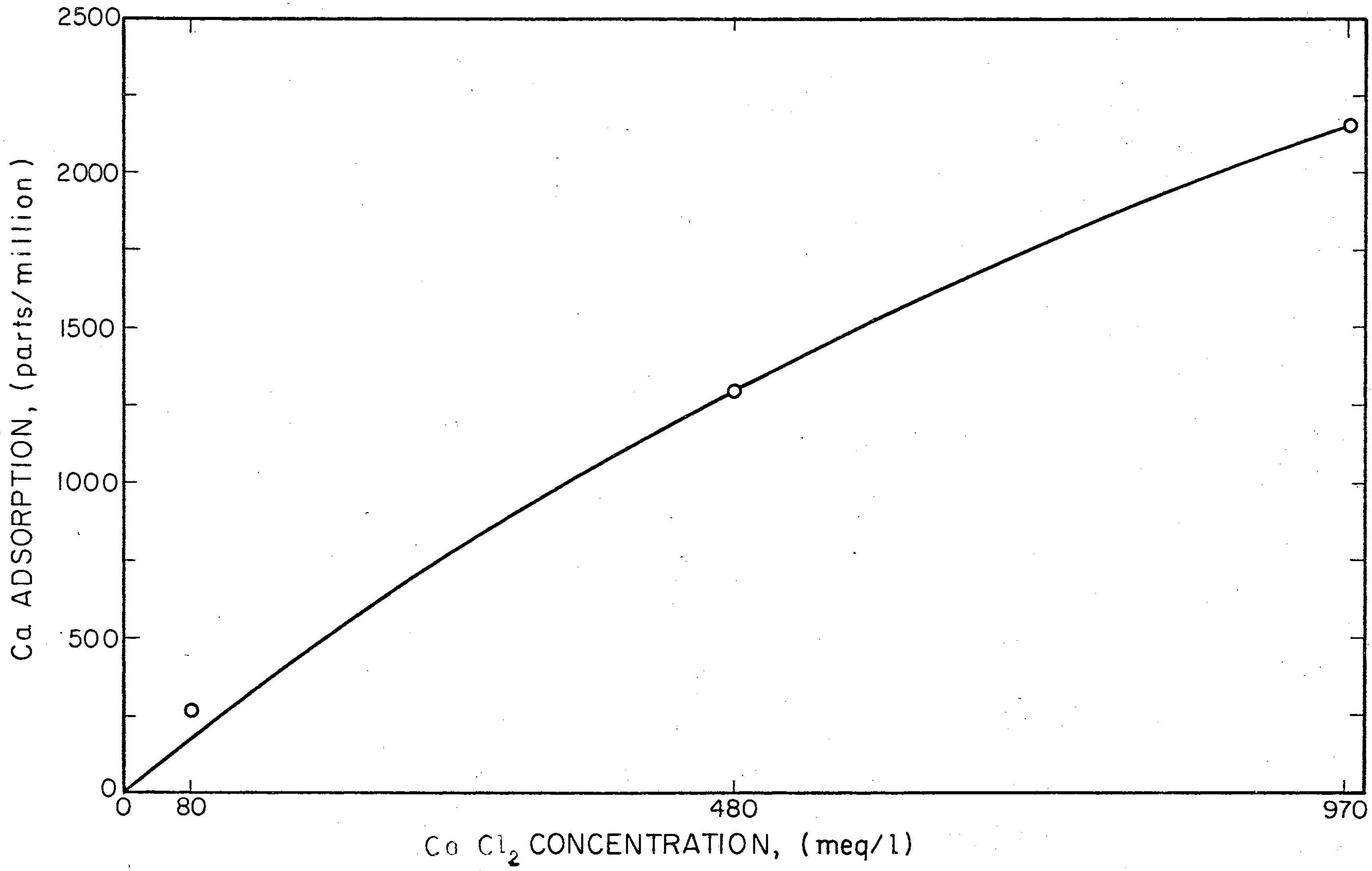


Figure 3. Adsorption of Calcium on Sodium-Saturated Norge Loam.

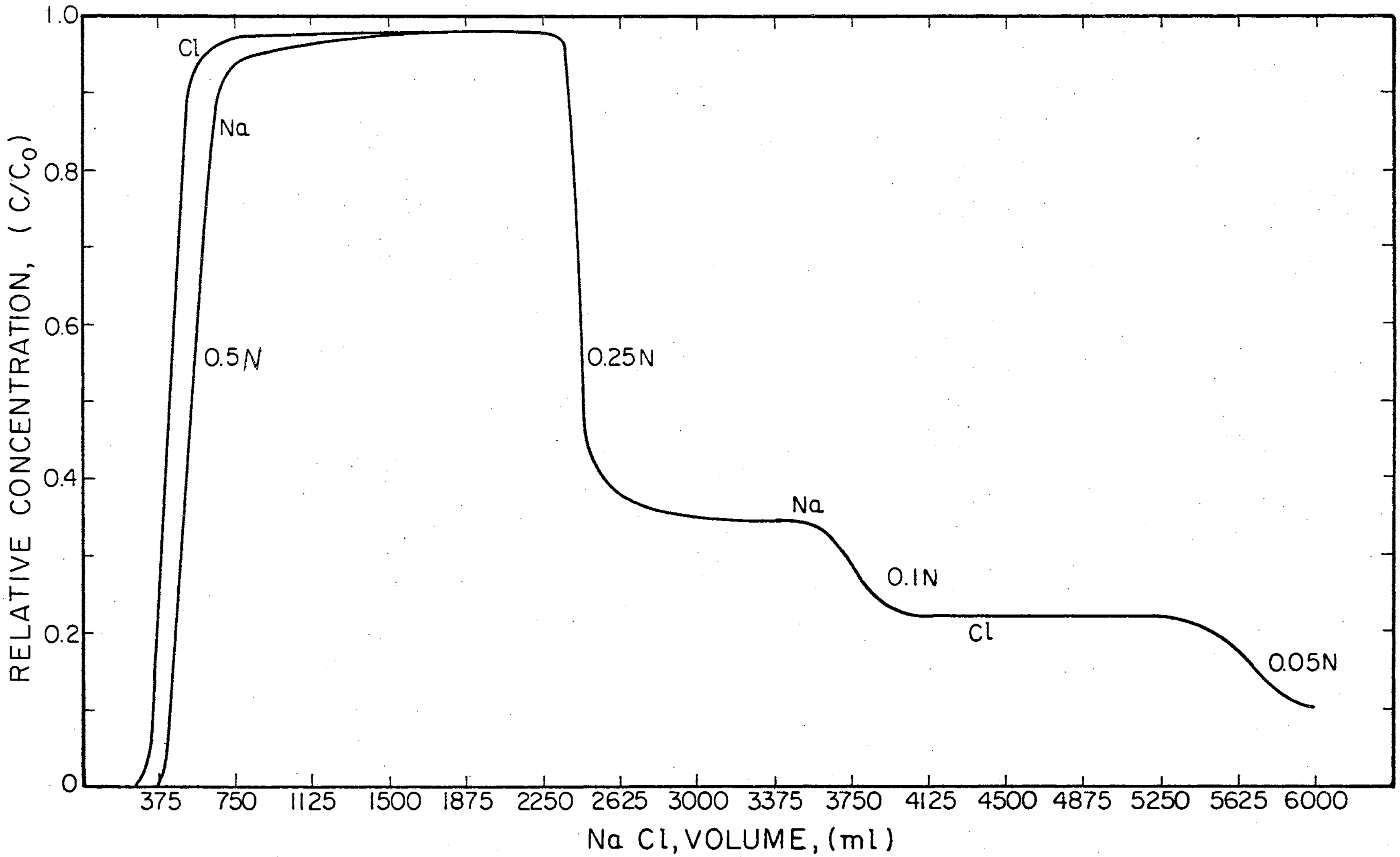


Figure 4. Relative Concentration of Sodium and Chloride in the Effluent. The Parameters Are The Concentration of the NaCl solution Added to The Soil.

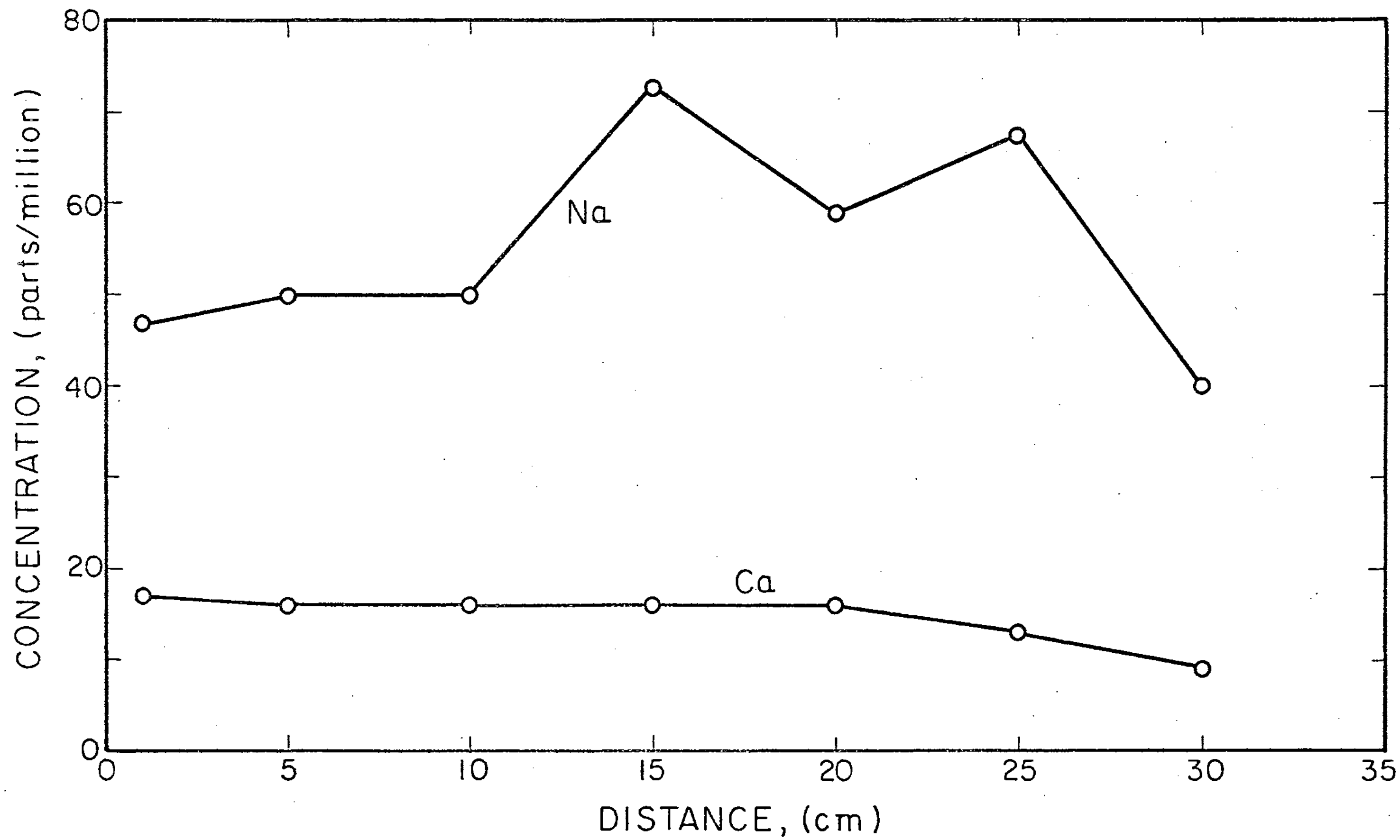


Figure 5. Calcium and Sodium Distribution in the Norge Loam After Various NaCl Solutions Had Passed Through the Soil. (Fig. 4).

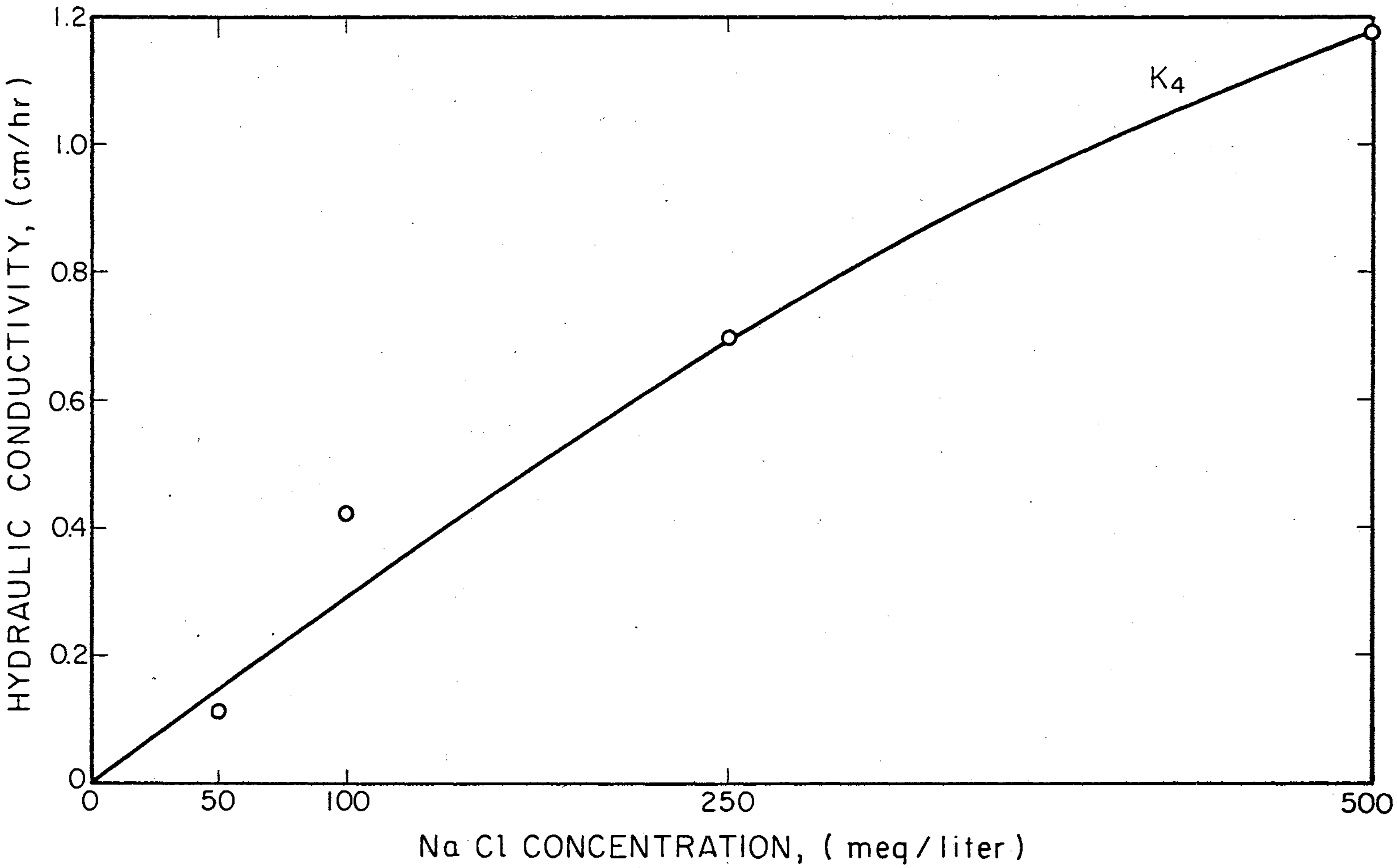


Figure 6. Hydraulic Conductivity Vs. Salt Concentration (SAR $=\infty$) for Norge Loam. $K_4$ is the Fourth Position in the Soil Column.

concentrations. As illustrated in this figure, the dilution of the concentration of the percolating solution is responsible for the decrease in hydraulic conductivity. It is evident from data in Tables IV, V, VI and VII in the Appendix that a sodium solution of high concentration (500 meq/l) could maintain a fairly high permeability, but as the sodium concentration decreases from 500 meq/l to 50 meq/l the soil tends to demonstrate a rather pronounced hydraulic conductivity decrease. Comparison of these results with those of Reeve and Doering (12) further accentuates the permeability-concentration relationship which depends highly upon the total salt concentration. The results are also in agreement with the work of Reeve and Tamaddoni (13) who indicate that permeability was a function of the salt solution and the sodium adsorption ratio of the percolating solution. The magnitude of the permeability depended upon the degree of flocculation or dispersion of the soil-water system and since a high concentration of sodium produces flocculation then it may increase or maintain a high hydraulic conductivity.

A 500 meq/l solution of sodium chloride does not really decrease the hydraulic conductivity of Ca saturated soil, but as the concentration of sodium chloride decreases the hydraulic conductivity decreases. However, the decrease was irreversible upon the reapplication of the initial solution (0.01N) calcium sulfate (Tables VIII and IX in the Appendix). This lack of reversibility may result from the calcium sulfate concentration being too low to cause any increase in the hydraulic conductivity. Also, as shown in Figure 7 the distribution of sodium through the soil column was still quite high indicating that insufficient time was given for the calcium to replace the sodium.

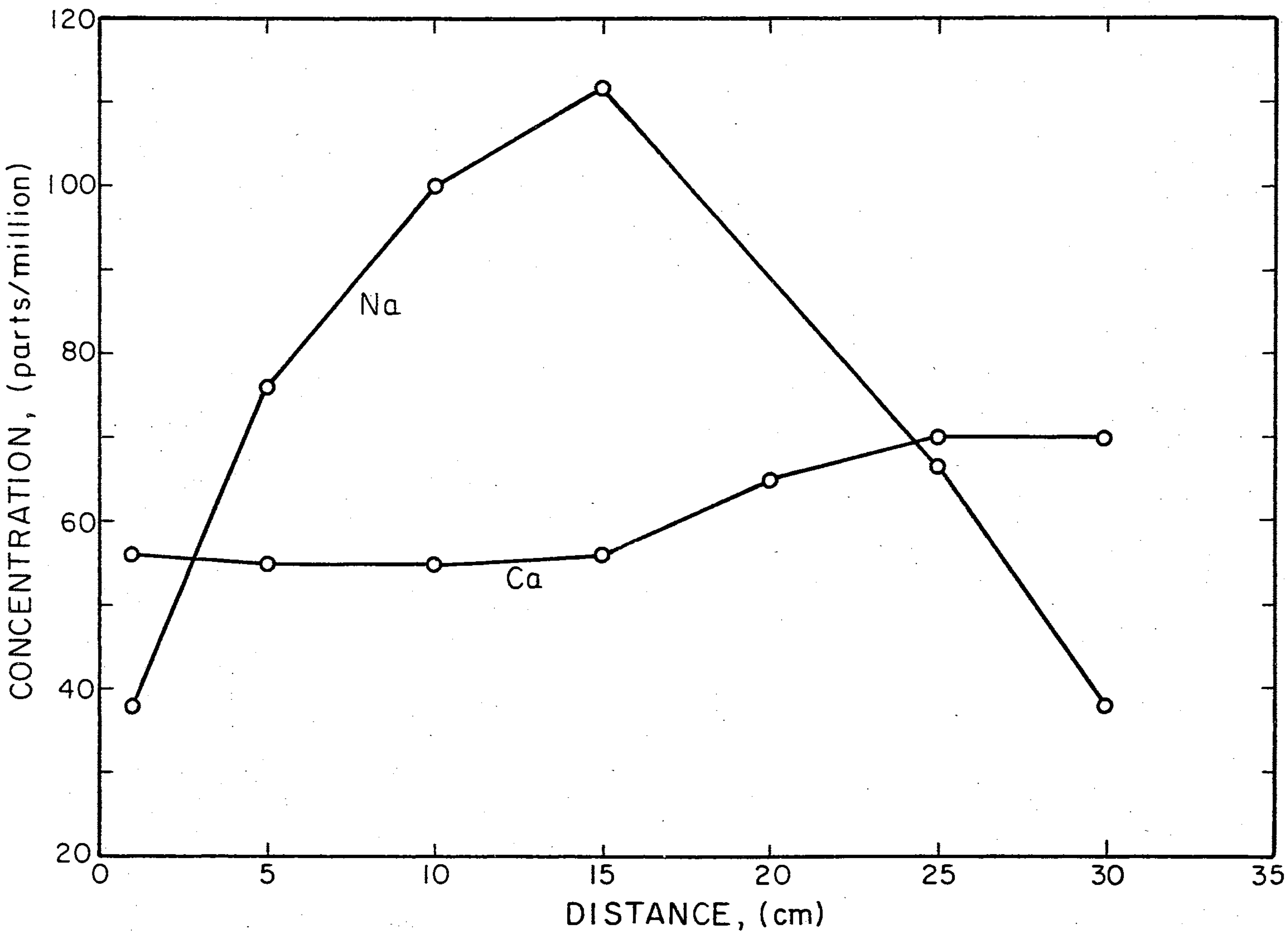


Figure 7. Calcium and Sodium Distribution in the Norge Loam Following $CaSO_4$ (0.01N) in a Sodium Saturated Soil.

B. Effects of Solution Concentration and Composition on Soil Permeability.

The changes in hydraulic conductivity resulting from different electrolyte concentrations and composition are shown in Figures 8 and 10. High salt-water dilution measurements were carried out using a mixture of $CaCl_2$ and NaCl and diluted to low concentrations (Table III).

Hydraulic conductivities through the soil column ($K_1$, $K_2$, $K_3$, $K_4$) were calculated at each concentration and are presented in Tables X, XI, XII, XIII in the Appendix and the results shown in Figure 8 reveal that the permeability of the soil remains almost constant for each of the four synthetized waters. Also, the distribution of calcium and sodium through the soil column presented in Figure 9 show that calcium concentration was higher than sodium in the soil-water system.

Other solutions of calcium and sodium at lower concentrations (Table II) were applied to the soil and the hydraulic conductivity measured. The data in Tables XIV, XV, and XVI in the Appendix show that as the total concentration of a mixed $CaCl_2$ and NaCl was decreased (while maintaining the concentration of calcium constant) the hydraulic conductivity values are decreased until the two ions calcium and sodium reach an equal concentration in the solution, then a sharp increase in hydraulic conductivity occurs (Fig. 10). This increase in permeability results from the replacement of sodium by calcium which produces flocculation of the soil. Soil column analysis for calcium and sodium distribution (Fig. 11) shows the progressive replacement of sodium by calcium.

The above results indicate that it should be possible to maintain the permeability of a soil regardless of the degree of sodium saturation

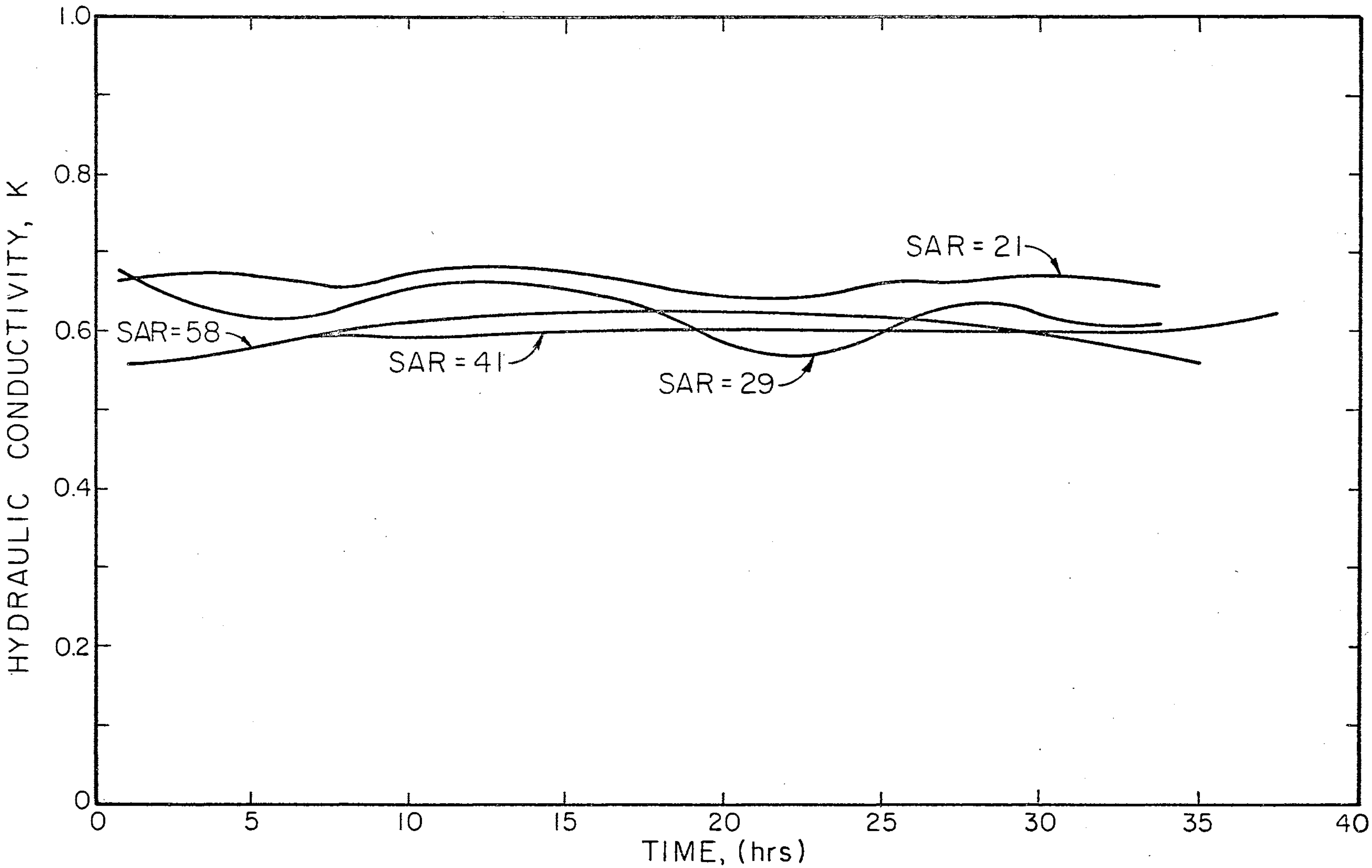


Figure 8. Change in Hydraulic Conductivity with Time at Different Salt Concentrations. (Table III).

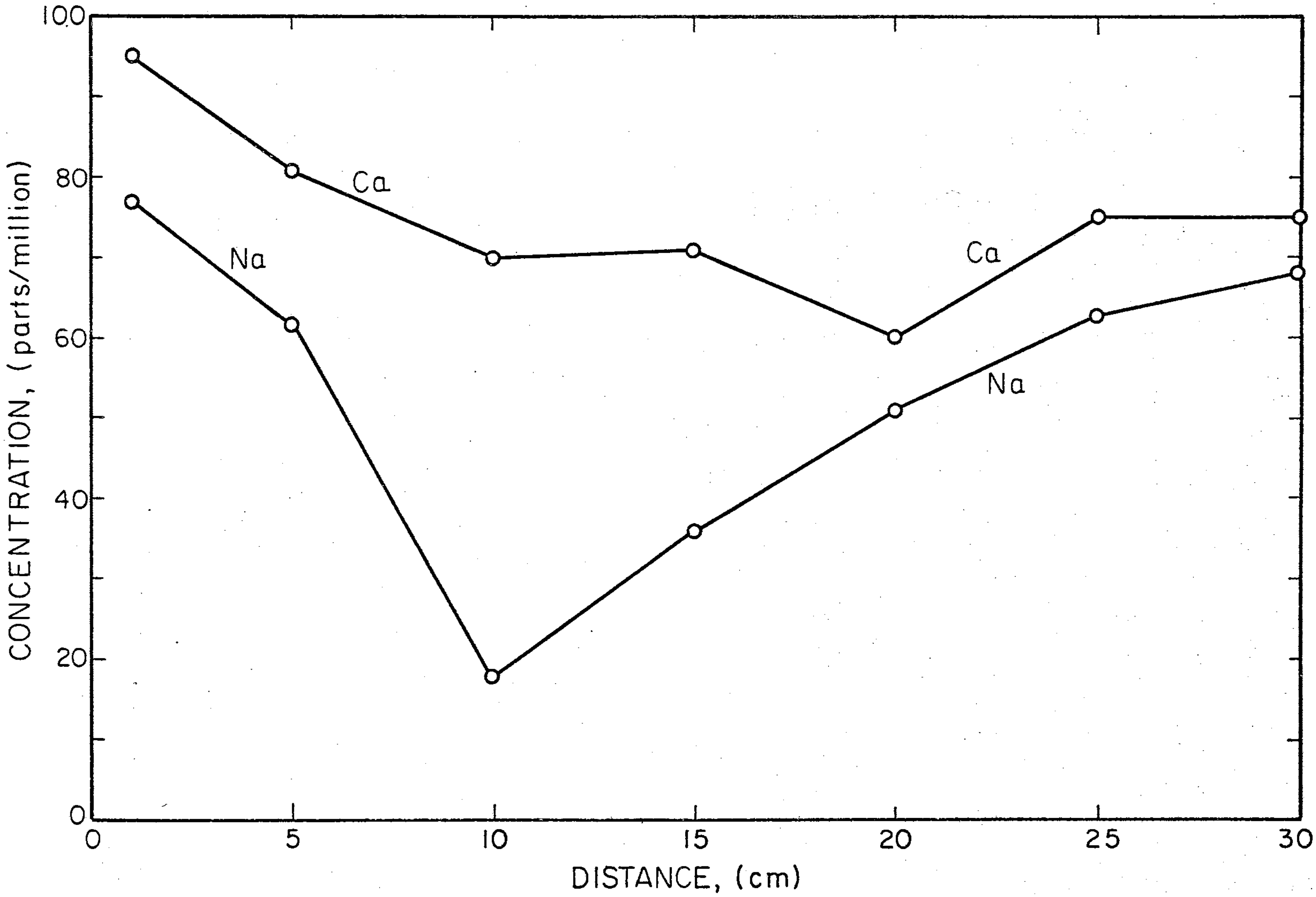


Figure 9. Calcium and Sodium Distribution in the Norge Loam After Various Mixtures of NaCl and CaCl Had Passed Through the Soil. (Fig. 8, Table III).

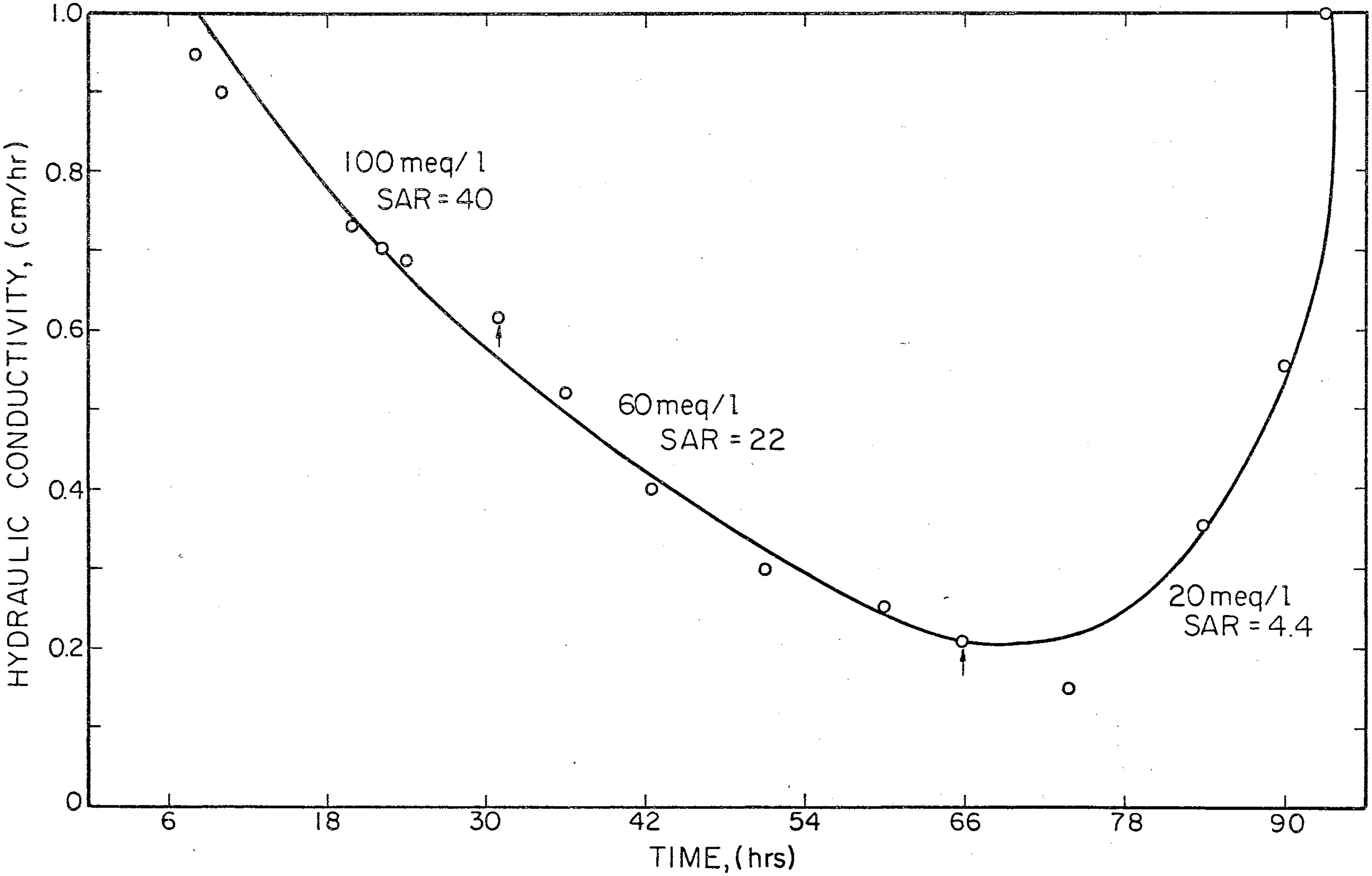


Figure 10. Change in Hydraulic Conductivity with Time at Various Salt Concentrations. (Table II).

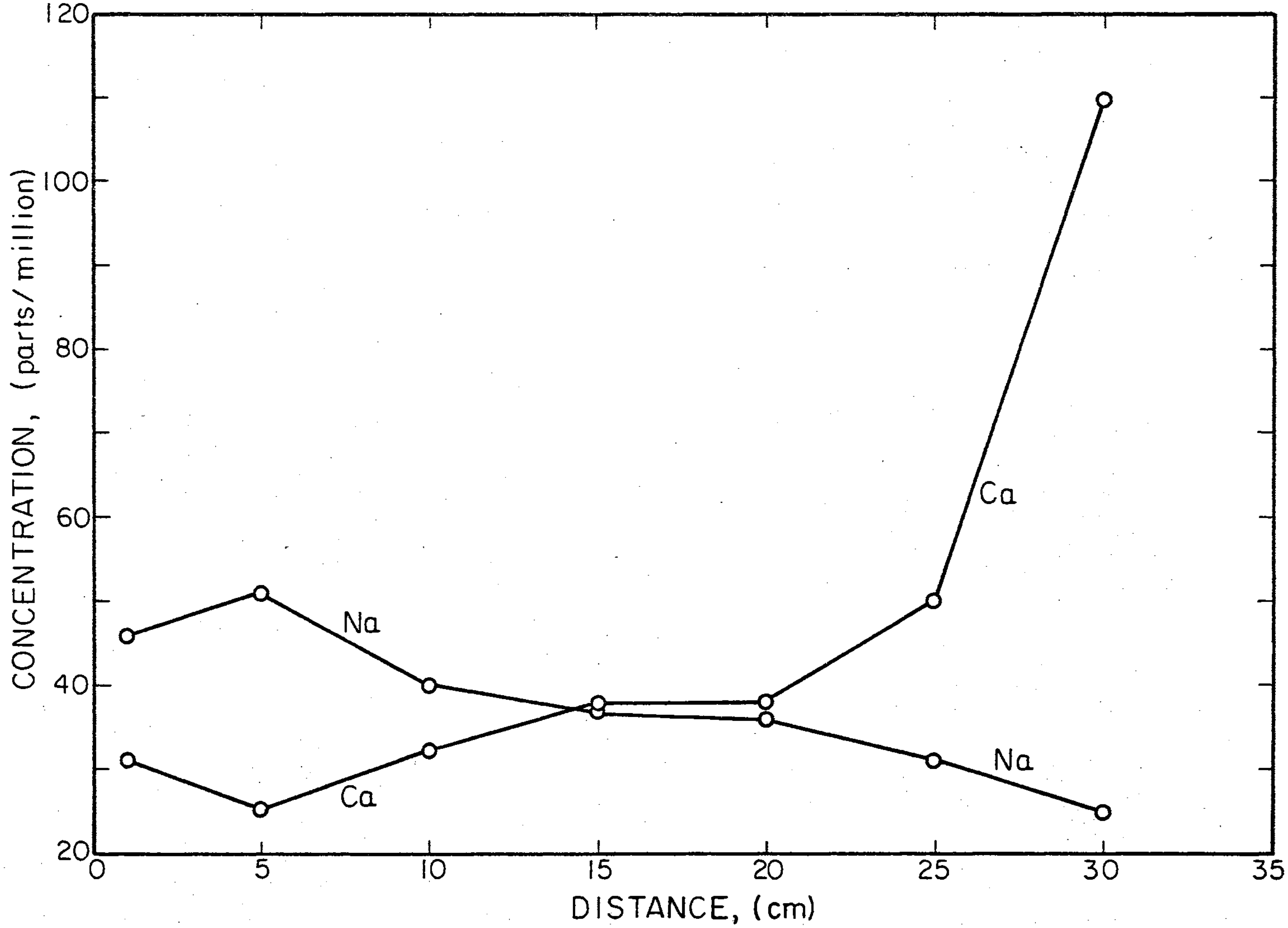


Figure 11. Calcium and Sodium Distribution in the Norge Loam After Various Mixtures of NaCl and CaCl had passed through the soil. (Fig. 10, Table II).

by using a solution of high electrolyte concentration. The addition of sodium salts to irrigation water as a flocculant and calcium chloride or other soluble calcium salts as a source of divalent cations will reclaim sodic soils. Quite obviously sea water could be one source of salts that may be used for this purpose. However, drainage must be adequate for the removal of the excess salts.

## CHAPTER V

## SUMMARY AND CONCLUSION

The effect of high sodium concentrated solution on the hydraulic conductivity of a calcium-saturated soil and sodium-saturated soil has been studied. Experimental data show that a high sodium concentration does not decrease the permeability of a previously calcium-saturated soil. The results indicate that hydraulic conductivity values of the Norge loam were dependent upon the total salt concentration and the kind of cations present. Experimental data strongly support the conclusion that the high sodium water was an effective method in maintaining high permeability in sodic soils. The results also indicate that it would be possible to maintain the permeability of a soil regardless of the degree of sodium saturation by using a sufficiently strong electrolyte solution. The addition of soluble calcium salts to the irrigation water as a reclamation for sodic soils can be efficient only if the soil is sufficiently permeable to get the calcium on the exchange complex.

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APPENDIX

TABLE IV

HYDRAULIC CONDUCTIVITY VALUES OF CALCIUM SATURATED NORGE LOAM
USING A 0.5N NaCl SOLUTION

| Hydraulic Conductivity cm/hr | Time (Units) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.5 | 1.33 | 2.0 | 6.0 | 16.5 | 20.30 | 26.66 | 33.33 | 46.6 | 53.33 | 60.0 | 66.6 |
| $K_1$ * | 1.99 | 1.99 | 1.99 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.1787 | 1.787 | 1.787 | 1.787 |
| $K_2$ | 1.544 | 1.41 | 1.415 | 1.415 | 1.415 | 1.425 | 1.425 | 1.358 | 1.213 | 1.213 | 1.213 | 1.213 |
| $K_3$ | 1.171 | 1.139 | 1.139 | 1.132 | 1.061 | 1.061 | 1.029 | 1.029 | 0.999 | 0.999 | 0.999 | 0.999 |
| $K_4$ | 1.415 | 1.415 | 1.415 | 1.36 | 1.30 | 1.35 | 1.35 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20, and 20-25 cm position along the column, respectively.

TABLE V

HYDRAULIC CONDUCTIVITY VALUES OF CALCIUM SATURATED SOIL UNDER THE FLOW OF (0.25N) NaCl SOLUTION

| Hydraulic Conductivity cm/hr | Time | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 3.76 | 7.4 | 10.33 | 12.21 | 17.0 | 25.40 | 34.0 | 42.38 | 46.23 | 50.38 |
| $K_1$ * | 1.787 | 1.54 | 1.69 | 1.69 | 1.69 | 1.45 | 1.45 | 1.45 | 1.450 | 1.450 |
| $K_2$ | 1.171 | 1.09 | .87 | 0.84 | 0.82 | 0.82 | 0.82 | 0.80 | 1.80 | 0.80 |
| $K_3$ | 0.57 | 0.97 | 0.89 | 0.77 | 0.679 | 0.65 | 0.58 | 0.58 | 1.585 | 0.585 |
| $K_4$ | 1.17 | 1.69 | 1.17 | 1.02 | 0.82 | 0.80 | 0.75 | 0.72 | 0.722 | 0.722 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20, and 20-25 cm position along the column, respectively.

TABLE VI

HYDRAULIC CONDUCTIVITY VALUES OF CALCIUM SATURATED SOIL UNDER THE FLOW OF (0.1N) NaCl SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5.86 | 12.33 | 15.5 | 19.2 | 21.0 | 24.5 | 27.05 | 29.0 | 39.6 | 44.6 | 45.83 | 52.83 | 67.11 |
| $K_1$* | 1.617 | 1.69 | 1.68 | 1.61 | 1.517 | 1.59 | 1.47 | 1.54 | 1.54 | 1.617 | 1.54 | 1.51 | 1.51 |
| $K_2$ | 0.87 | 0.77 | 0.72 | 0.69 | 0.693 | 0.693 | 0.66 | 0.66 | 0.66 | 0.606 | 0.606 | 0.606 | 0.60 |
| $K_3$ | 0.595 | 0.558 | 0.547 | 0.44 | 0.441 | 0.432 | 0.404 | 0.36 | 0.36 | 0.36 | 0.34 | 0.34 | 0.343 |
| $K_4$ | 0.738 | 0.722 | 0.60 | 0.56 | 0.535 | 0.522 | 0.514 | 0.46 | 0.46 | 0.46 | 0.44 | 0.441 | 0.441 |

*$K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE VII

HYDRAULIC CONDUCTIVITY VALUES OF CALCIUM SATURATED SOIL UNDER THE FLOW OF (0.05N) NaCl SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2.61 | 6.05 | 12.9 | 21.06 | 27.8 | 37.8 | 45.2 | 52.2 | 58.5 | 60.17 | 68 |
| $K_1$* | 1.41 | 1.132 | 0.85 | 0.77 | 0.69 | 0.54 | 0.606 | 0.585 | 0.575 | 0.573 | 0.56 |
| $K_2$ | 0.849 | 0.77 | 0.46 | 0.404 | 0.36 | 0.345 | 0.336 | 0.336 | 0.339 | 0.339 | 0.337 |
| $K_3$ | 0.36 | 0.33 | 0.24 | 0.169 | 0.14 | 0.121 | 0.112 | 0.112 | 0.115 | 0.115 | 0.117 |
| $K_4$ | 0.45 | 0.43 | 0.37 | 0.25 | 0.22 | 0.176 | 0.138 | 0.138 | 0.132 | 0.13 | 0.125 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE VIII

HYDRAULIC CONDUCTIVITY VALUES OF CALCIUM SATURATED SOIL UNDER THE FLOW OF (0.1N) NaCl SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2.4 | 5.0 | 9.3 | 16.0 | 24.0 | 26.5 | 30.5 | 40.0 | 42.7 | 45.3 | 51.2 | 64.2 | 70.5 |
| $K_1$* | 0.653 | 0.64 | 0.607 | 0.602 | 0.60 | 0.585 | 0.56 | 0.54 | 0.52 | 0.52 | 0.51 | 0.51 | 0.51 |
| $K_2$ | 0.606 | 0.603 | 0.52 | 0.485 | 0.47 | 0.47 | 0.46 | 0.45 | 0.45 | 0.446 | 0.42 | 0.414 | 0.404 |
| $K_3$ | 0.507 | 0.445 | 0.45 | 0.409 | 0.402 | 0.40 | 0.40 | 0.40 | 0.399 | 0.39 | 0.377 | 0.357 | 0.353 |
| $K_4$ | 0.478 | 0.459 | 0.44 | 0.431 | 0.424 | 0.41 | 0.409 | 0.39 | 0.39 | 0.377 | 0.377 | 0.373 | 0.365 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE IX

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL DURING APPLICATION OF 0.01N $CaSO_4$

| Hydraulic Conductivity cm/hr | Time (hrs.) 2.07 | 5.0 | 15.0 |
|---|---|---|---|
| $K_1$* | 0.424 | 0.419 | 0.414 |
| $K_2$ | 0.343 | 0.339 | 0.333 |
| $K_3$ | 0.342 | 0.340 | 0.339 |
| $K_4$ | 0.36 | 0.357 | 0.349 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE X

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$(0.13N) AND NaCl(0.47N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) 2.3 | 3.8 | 7.25 | 27.2 | 29.2 | 31.37 | 34.48 | 37.16 |
|---|---|---|---|---|---|---|---|---|
| $K_1$* | 0.576 | 0.58 | 0.60 | 0.63 | 0.63 | 0.54 | 0.558 | 0.54 |
| $K_2$ | 0.70 | 0.58 | 0.51 | 0.558 | 0.90 | 0.93 | 0.648 | 0.714 |
| $K_3$ | 0.57 | 0.62 | 0.68 | 0.714 | 0.55 | 0.534 | 0.558 | 0.522 |
| $K_4$ | 0.67 | 0.71 | 0.78 | 0.88 | 0.64 | 0.55 | 0.534 | 0.576 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE XI

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$(0.065N) AND NaCl(0.235N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 8.3 | 10.0 | 11.0 | 20.0 | 24.0 | 35.0 | 37.0 |
| $K_1$* | 0.63 | 0.588 | 0.588 | 0.612 | 0.60 | 0.60 | 0.548 |
| $K_2$ | 0.67 | 0.78 | 0.684 | 0.702 | 0.648 | 0.588 | 0.66 |
| $K_3$ | 0.67 | 0.534 | 0.558 | 0.570 | 0.576 | 0.588 | 0.516 |
| $K_4$ | 0.88 | 0.588 | 0.588 | 0.684 | 0.714 | 0.672 | 0.90 |

*$K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE XII

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$(0.032N) AND NaCl(0.118N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.5 | 6.56 | 10.6 | 17.56 | 18.70 | 22.6 | 24 | 25.6 | 27.33 | 30.21 | 31.50 |
| $K_1$* | 0.684 | 0.60 | 0.66 | 0.672 | 0.612 | 0.57 | 0.59 | 0.60 | 0.63 | 0.62 | 0.60 |
| $K_2$ | 0.63 | 0.522 | 0.67 | 0.63 | 0.63 | 0.54 | 0.52 | 0.52 | 0.54 | 0.498 | 0.57 |
| $K_3$ | 0.534 | 0.49 | 0.48 | 0.57 | 0.522 | 0.48 | 0.48 | 0.48 | 0.46 | 0.48 | 0.43 |
| $K_4$ | 0.78 | 0.63 | 0.86 | 0.78 | 0.66 | 0.58 | 0.57 | 0.60 | 0.64 | 0.57 | 0.55 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 2-025 cm position along the column, respectively.

TABLE XIII

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$ (0.016N) AND NaCl(0.059N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) 3.0 | 4.76 | 7.96 | 14.8 | 22.5 | 27.8 | 29.55 | 33.6 |
|---|---|---|---|---|---|---|---|---|
| $K_1$* | 0.67 | 0.67 | 0.65 | 0.68 | 0.64 | 0.66 | 0.67 | 0.906 |
| $K_2$ | 0.84 | 0.78 | 0.73 | 0.66 | 0.63 | 0.612 | 0.63 | 0.63 |
| $K_3$ | 0.57 | 0.558 | 0.52 | 0.49 | 0.49 | 0.612 | 0.498 | 0.498 |
| $K_4$ | 0.79 | 0.78 | 0.68 | 0.74 | 0.68 | 0.57 | 0.702 | 0.702 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE XIV

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$ (0.01N) AND NaCl (0.09N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) 2.66 | 3.66 | 4.5 | 5.3 | 6.1 | 8.8 | 10.0 | 18.4 | 19.8 | 20.8 | 22.3 | 24.7 | 26 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $K_1^*$ | 1.30 | 1.30 | 1.25 | 1.21 | 1.21 | 0.94 | 0.91 | 0.84 | 0.73 | 0.70 | 0.70 | 0.69 | 0.67 | 0.62 |
| $K_2$ | 1.09 | 1.09 | 1.12 | 1.09 | 0.87 | 0.87 | 0.87 | 0.87 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 | 0.86 |
| $K_3$ | 3.08 | 3.08 | 3.08 | 3.08 | 3.08 | 1.95 | 1.88 | 1.88 | 1.88 | 1.88 | 1.88 | 1.78 | 1.78 | 1.54 |
| $K_4$ | 0.8 | 0.8 | 0.72 | 0.66 | 0.66 | 0.66 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the columns, respectively.

TABLE XV

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$ (0.01N) AND NaCl (0.05N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4.5 | 12.0 | 14.0 | 17.0 | 19.0 | 20.0 | 22.0 | 24.0 | 26.0 | 27.0 | 35.5 |
| $K_1$* | 0.52 | 0.40 | 0.37 | 0.31 | 0.30 | 0.30 | 0.27 | 0.26 | 0.26 | 0.26 | 0.21 |
| $K_2$ | 0.84 | 0.61 | 0.56 | 0.47 | 0.41 | 0.41 | 0.37 | 0.34 | 0.32 | 0.32 | 0.25 |
| $K_3$ | 1.61 | 1.47 | 1.61 | 1.47 | 1.41 | 1.35 | 1.21 | 1.17 | 1.17 | 1.17 | 0.84 |
| $K_4$ | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

TABLE XVI

HYDRAULIC CONDUCTIVITY VALUES OF SODIUM SATURATED SOIL UNDER THE FLOW OF A MIXTURE OF $CaCl_2$ (0.01N) AND NaCl (0.01N) SOLUTION

| Hydraulic Conductivity cm/hr | Time (hrs.) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.5 | 4.3 | 5.7 | 6.6 | 7.6 | 10.0 | 18.0 | 24.3 | 26.0 | 27.0 | 30.0 | 31.3 |
| $K_1$* | 0.21 | 0.21 | 0.21 | 0.18 | 0.15 | 0.31 | 0.36 | 0.56 | 0.85 | 1.02 | 3.75 | 16.9 |
| $K_2$ | 0.23 | 0.21 | 0.20 | 0.20 | 0.25 | 0.23 | 0.22 | 0.17 | 0.17 | 0.16 | 0.14 | 0.14 |
| $K_3$ | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.84 | 0.64 | 0.50 | 0.48 | 0.48 | 0.45 | 0.45 |
| $K_4$ | 0.99 | 0.99 | 1.02 | 1.05 | 1.21 | 1.21 | 1.09 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 |

* $K_1$, $K_2$, $K_3$ and $K_4$ are the hydraulic conductivities between 5-10, 10-15, 15-20 and 20-25 cm position along the column, respectively.

VITA

2.

Habib Hizem

Candidate for the Degree of

Master of Science

Thesis: THE EFFECT OF SALT CONCENTRATION AND COMPOSITION ON SOIL HYDRAULIC CONDUCTIVITY

Major Field: Agronomy

Biographical:

Personal Data: Born in Monastir, Tunisia, March 3, 1937, the son of Mr. and Mrs. Mohamed Hizem.

Education: Graduated from Agriculture High School, Moghrane, Tunisia in June 1960; received the Bachelor of Science degree from Oklahoma State University in 1964; completed requirements for the Master of Science degree at Oklahoma State University in May, 1969 with a major in Agronomy.

Experience: Worked for Soil Conservation Service in Oklahoma in the summer of 1961, 1962 and 1963. Employed as Agricultural Officer in Ministry of Agriculture for the planning of Oued Merguellil Watershed Project in Tunisia in March, 1964.